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A new process has been developed for removing sulfur from coal (as power plant fuel) during the combustion phase. In this process, coal is dissolved by injection into molten iron and simultaneously the dissolved coal carbon is oxidized with injected air to carbon monoxide. Under the reducing conditions existing during combustion, coal sulfur is not oxidized, but transferred from the iron to a slag consisting of coal ash and added limestone. Thus, a sulfur-free offgas is produced for use in power plant boilers. Experimental combustor studies have shown that a boiler stack gas, containing less than 50 ppm sulfur dioxide is produced. Results indicate total coal solubility is obtained at injection depths of less than three feet; and total oxygen utilization results at air injection depths of 5 inches. Combustor design parameters were established, and indicate that three 38-foot I.D. combustors are required for a 1000 MW plant. Laboratory work has shown the slags can be successfully desulfurized with steam to produce elemental sulfur and a H_2S/SO_2 gas stream suitable for additional elemental sulfur recovery in a Claus Plant. Process economics are favorable, indicating; that a retrofitted installation would cost $23/KW, and that incorporation into a grass roots, gas-fired power station would have a capital cost increase of only $1.5/KW over a SO_2-polluting coal-fired plant.

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SO_2 FREE TWO-STAGE COAL COMBUSTION PROCESS

by

Applied Technology Corporation
135 Delta Drive
Pittsburgh, Pennsylvania 15238

for the

ENVIRONMENTAL PROTECTION AGENCY

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EPA Project Officer

Mr. Douglas A. Kemnitz, of the Control Systems Laboratory Division was the EPA project officer for the work discussed in this report. Mr. Stanley A. Bunas is the EPA project officer of the continuation of this work.

ABSTRACT

Under EPA sponsorship, (Contract No. CPA 70-146) Applied Technology Corporation is developing a new SO_2-free Two-Stage Coal Combustion Process. In this process, coal is dissolved by injection into molten iron and simultaneously the dissolved coal carbon is oxidized with injected air to carbon monoxide. Under the reducing conditions existing during combustion, coal sulfur is not oxidized, but transferred from the iron to a slag consisting of coal ash and added limestone. Thus, a sulfur-free offgas (carbon monoxide, hydrogen, and nitrogen) is produced for use in power plant boilers.

Experimental combustor studies have shown that a boiler stack gas, containing less than 50 ppm sulfur dioxide is produced. Results indicate total coal solubility is obtained at injection depths of less than three feet; and total oxygen utilization results at air injection depths of 5 inches. Combustor design parameters were established, and indicate that three 38-foot I.D. combustors are required for a 1000 MW plant. Laboratory work has shown the slags can be successfully desulfurized with steam to produce elemental sulfur and a H_2S/SO_2 gas stream suitable for additional elemental sulfur recovery in a Claus Plant.

Process economics are favorable, indicating that a retrofitted installation would cost $23/KW. If the process is incorporated into a grass roots, gas-fired power station, the capital cost increase would be only $1.5/KW over a SO_2-polluting coal-fired plant. Operating costs for this new facility would be comparable to polluting plants and considerably less if SO_2 abatement equipment is included in the polluting coal-fired facility.

This report was submitted in partial fulfillment of Contract No. CPA 70-146 under the sponsorship of the Environmental Protection Agency.

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CONCLUSIONS

Analysis of the results obtained to date leads to the following conclusions about the Two-Stage Coal Combustion Process:

1. Boiler stack gas containing less than 50 ppm SO_2 can be attained, regardless of coal sulfur content.

2. Combustor design parameters have been established: three 38-ft diameter combustors can comfortably fuel a 1,000 megawatt power plant. For complete dissolution, the coal should be injected 3 feet under the molten iron surface; for complete utilization, the air should be injected 5 inches below the molten iron surface.

3. Combustor slags can be desulfurized with steam to produce elemental sulfur and a mixture of H_2S and SO_2 suitable for elemental sulfur recovery in a Claus plant.

4. The capital cost for the additional equipment required for this process is approximately $23 per kilowatt. In a new installation, equipment savings result in a capital cost of only $1.5 per kilowatt above the cost of a SO_2 polluting conventional coal fired plant. Operating costs for such a new facility would be comparable to those of polluting conventional plants.

RECOMMENDATIONS

The work described in this report provides the basic carburization and decarburization rate information required for combustor design. The results of this work also show that sulfur dioxide emissions from the power plant stack will be extremely low (less than 50 ppm).

The successful conclusion of the above basic studies has led to additional experimental studies. A study of safe, non-water cooled, lances for coal and air injection into the combustor is underway. Also planned as part of the current program is a series of more detailed studies on selected key areas. These include (1) simultaneous carburization and decarburization of the iron bath to more closely approximate commercial operation, (2) improved measurement of particulate emissions, (3) prolonged "endurance" runs to obtain more reliable refractory life estimates, (4) rapid desulfurization of high temperature liquid slag, (5) determination of sulfur bearing slag weathering characteristics, (6) exploration of trace element accumulation in the iron bath, (7) review of the data by design engineers to determine indicated additions or changes in the experimental program, and (8) boilermaker-oriented study of combustor offgas utilization.

Essentially, the work completed and planned for the experimental phase will provide all the answers that can be obtained from the scale of equipment (28 inch diameter combustor) that has been used to date. Since the data are most encouraging, both from the technical and from the economic feasibility point of view, a pilot-demonstration combustor operation is indicated as the next step. This installation should be operated in conjunction with a 50 megawatt to 150 megawatt boiler. An estimate of the cost of a 30-month program, including 9 to 12 months of continuous operation of the combustor providing all of the fuel for a commercial boiler, has been prepared. The cost of the project will depend on the size of the installation, and will vary from $5.5 million for a 50 megawatt unit to $13 million for a 150 megawatt unit.

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INTRODUCTION

Because of the large quantities emitted into the atmosphere, sulfur dioxide is regarded as the most serious gaseous air pollutant and the need to eliminate it from power plant flue gases has been well documented. To minimize sulfur dioxide emissions, some power plants may operate on natural gas or low-sulfur fuel oil. However, the high cost and limited availability of these fuels necessitate the power industry's dependence on coal as its primary fuel.

A few power plants are located near western low sulfur coal deposits. However, the high cost of transportation of low sulfur coal to the industrialized east precludes the use of such coal on a large scale. Consequently, considerable money and research efforts have been expended to develop a practical method for high-sulfur coal combustion without sulfur dioxide emissions from power plant stacks.

In general, the problem has been approached from two directions, i.e., the removal of sulfur prior to combustion and the removal of sulfur dioxide from the flue gases after the sulfur bearing coal has been burned. The precombustion sulfur removal processes are either very expensive (de-ashed coal) or are ineffective (beneficiation and washing techniques) for lowering coal sulfur content to desired levels. On the other end of the scale, the treatment of flue gases to remove sulfur dioxide has thus far proven to be rather expensive or inoperable. These processes, such as scrubbing, limestone and/or dolomite injection, or sorption techniques inherently become expensive because of the dilute sulfur dioxide concentration and the large volume of gases that must be treated.

For these reasons, the Applied Technology Corporation (ATC) has developed a process for removing sulfur (while it is still in concentrated form) during the actual combustion phase. Thus, unlike other processes, the ATC coal gasifier prevents the sulfur from oxidizing and removes it during the coal gasification phase.

Essentially, the ATC process consists of injecting coal particles into a molten bath of iron. Because iron in the liquid state has a tremendous affinity for sulfur and carbon, the coal solubilizes to release organic and inorganic sulfur constituents for reaction with the active iron melt. Iron sulfides are formed which then migrate to a lime containing slag floating on the molten iron bath (much like a steelmaking practice) where they are removed from the combustion process. At the same time, the carbon that is dissolved in the molten iron is reacted with air to produce an offgas which consists of nitrogen, carbon monoxide, and hydrogen. This hot (above 2500°F) gaseous mixture, essentially free of sulfur dioxide, is introduced into a steam boiler along with secondary air to recover all of the heating value of the coal. Sulfur is recovered in elemental form from the slag produced in the ATC process, along with iron contained from the coal pyrites and a desulfurized slag

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road aggregate. All three by-products have commercial value.

The Office of Air Programs of the Environmental Protection Agency is sponsoring (Contract No. CPA 70-146) a study in which ATC has been obtaining experimental data from a coal gasifier of about 2 megawatt capacity. The results of this work have been extremely encouraging in that the use of molten iron to solubilize coal and then burn it produces a hot offgas essentially sulfur-free that is suitable for power plant boilers or gas turbines.

This report presents a description of the process, a discussion of the state of the art, a program for additional work required to demonstrate the process on a commercial scale, and the cost of the proposed demonstration work.

PROCESS DESCRIPTION

Combustor Concept

What for years has been a problem in the steel industry can be a boon for the energy industries. The strong affinity that exists between iron and sulfur making it difficult to produce low-sulfur iron and steel is the basis of the combustion-gasification concept. Instead of combusting or gasifying coal by conventional techniques which convert the coal sulfur into sulfur dioxide, in this new method, coal is injected into a mass of molten iron. Both the fixed carbon and sulfur contained in the coal are retained by the iron. That is, the fixed carbon content of the coal sulfur are solubilized in the iron, while the coal volatiles are cracked and exit in the offgas. This is termed carburization and is represented as follows:

$$\underset{\text{Coal}}{(\text{Fixed Carbon})} \xrightarrow{\text{dissolves}} \underset{\text{Iron}}{(\text{Carbon})}$$

$$\underset{\text{Coal}}{(\text{Organic and Inorganic Sulfur})} \xrightarrow{\text{dissolves}} \underset{\text{Iron}}{(\text{Sulfur})}$$

$$\underset{\text{Coal}}{(\text{Volatiles})} \xrightarrow{\text{crack}} \underset{\text{Offgas}}{(CO,\ CH_4,\ H_2)}$$

The dissolved carbon in the iron is then gasified by reaction with air or oxygen to yield carbon monoxide. This is termed decarburization and is represented as follows:

$$\underset{\text{Iron}}{(\text{Carbon})} + \underset{\text{Air}}{(1/2\ O_2)} \longrightarrow \underset{\text{Offgas}}{(CO)}$$

By equalizing the carburization and decarburization rates, defined as the weight percent change of carbon in iron per minute, a steady state carbon level in the bath can be maintained. Thus, the combustor-gasification principle involves the simultaneous carburization with coal and decarburization with air of a molten iron bath to produce a sulfur-free carbon monoxide rich offgas.

The dissolved coal sulfur in the iron migrates to a lime-bearing slag layer floating on the molten iron to form calcium sulfide as follows:

$$\underset{\text{Iron}}{(\text{Sulfur})} + \underset{\text{Slag}}{(CaO)} \longrightarrow \underset{\text{Slag}}{(CaS)} + \underset{\text{Iron}}{(1/2\ O_2)}$$

Thus, sulfur is continuously removed from the iron into a slag. The slag consists of lime, silica, alumina, and calcium sulfide. Limestone is continually added to the system, whereas, silica and alumina occur in the coal ash:

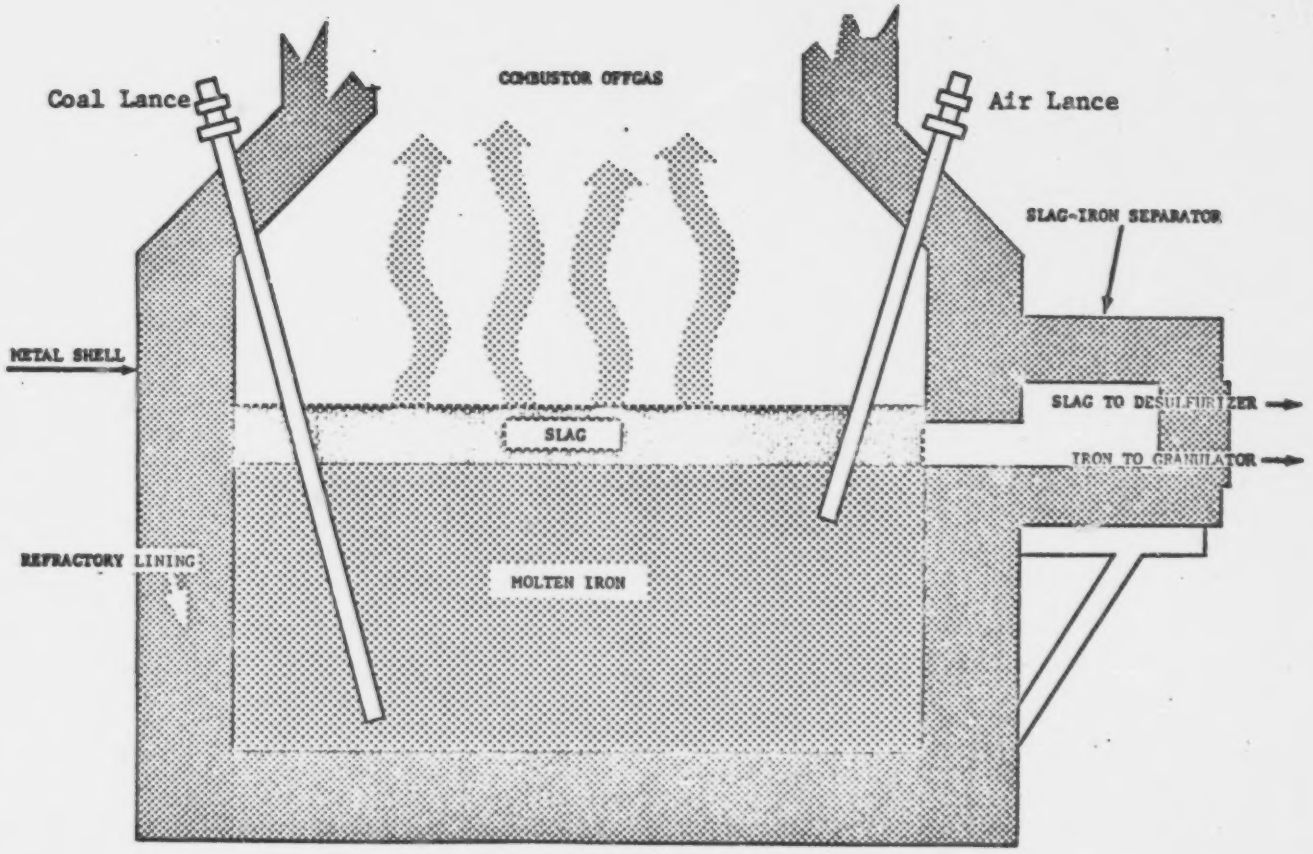

FIGURE 1-CONCEPTUAL DESIGN OF COMBUSTOR

$$\underset{\text{Coal}}{(\text{Ash})} \longrightarrow \underset{\text{Slag}}{(\text{Silica and Alumina})}$$

The calcium sulfide bearing slag is continuously removed and desulfurized with steam to yield a sulfur bearing offgas and desulfurized slag:

$$\underset{\text{Slag}}{(\text{CaS})} + \text{Steam} \longrightarrow \underset{\text{Desulfurized Slag}}{(\text{CaO})} + \underset{\text{Offgas}}{(\text{S}, H_2S, SO_2)}$$

A portion of the desulfurized slag is recycled to the iron to utilize its lime content and the rest is removed from the system. The sulfur from the desulfurization offgas is condensed out and the H_2S - SO_2 gas mixture is sent to a Claus plant for sulfur recovery.

The ATC coal gasification method produces a sulfur-free, carbon monoxide rich offgas, marketable sulfur, and coal ash-bearing desulfurized slag. The iron normally found in coal accumulates in the bath, which is periodically trapped for by-product iron credit. No pollution causing by-products are formed and, because desulfurized lime bearing slag is recycled, considerably less than the stoichiometric requirement of limestone (for sulfur removal) is required. Also, a number of carbonaceous materials, from petroleum coke to sub-bituminous coals, with a wide range of sulfur and ash contents, can be gasified.

A conceptual drawing of a furnace structure for the submerged combustion of coal which would be compatible with conventional boilers used in power generating plants is shown in Figure 1. As shown, the combustor is a cylindrical refractory-lined vessel which contains a molten iron bath into which coal is continuously injected beneath the surface. Located above the combustor is a transition section which connects the combustor to a conventional boiler (not shown).

As indicated in Figure 1, the sulfur-bearing coal is injected into the molten iron where it dissolves. The combustion of carbon from the coal by addition of air near the iron bath surface produces a hot carbon-monoxide rich offgas (2500-2700°F) which proceeds via a transition section to the conventional boiler where it is further combusted (to carbon dioxide) to yield additional heat.

The operation of the combustor requires limestone and/or lime-bearing slag. Limestone is converted to lime in the combustor and forms a slag, which has an affinity for sulfur and thus removes the sulfur from the molten iron. The slag is removed from the combustor and sent to a desulfurizer where sulfur is recovered. A portion of the slag is fed back to the combustor to again remove sulfur from the iron.

The Overall Coal Gasification Process

Figure 2 shows a diagram of the entire process. Coal from storage is crushed and pneumatically conveyed into the combustor through tubes (lances). Recycled desulfurized slag and limestone are added to the coal and proportioned to the coal lances. Air for combustion and pneumatic

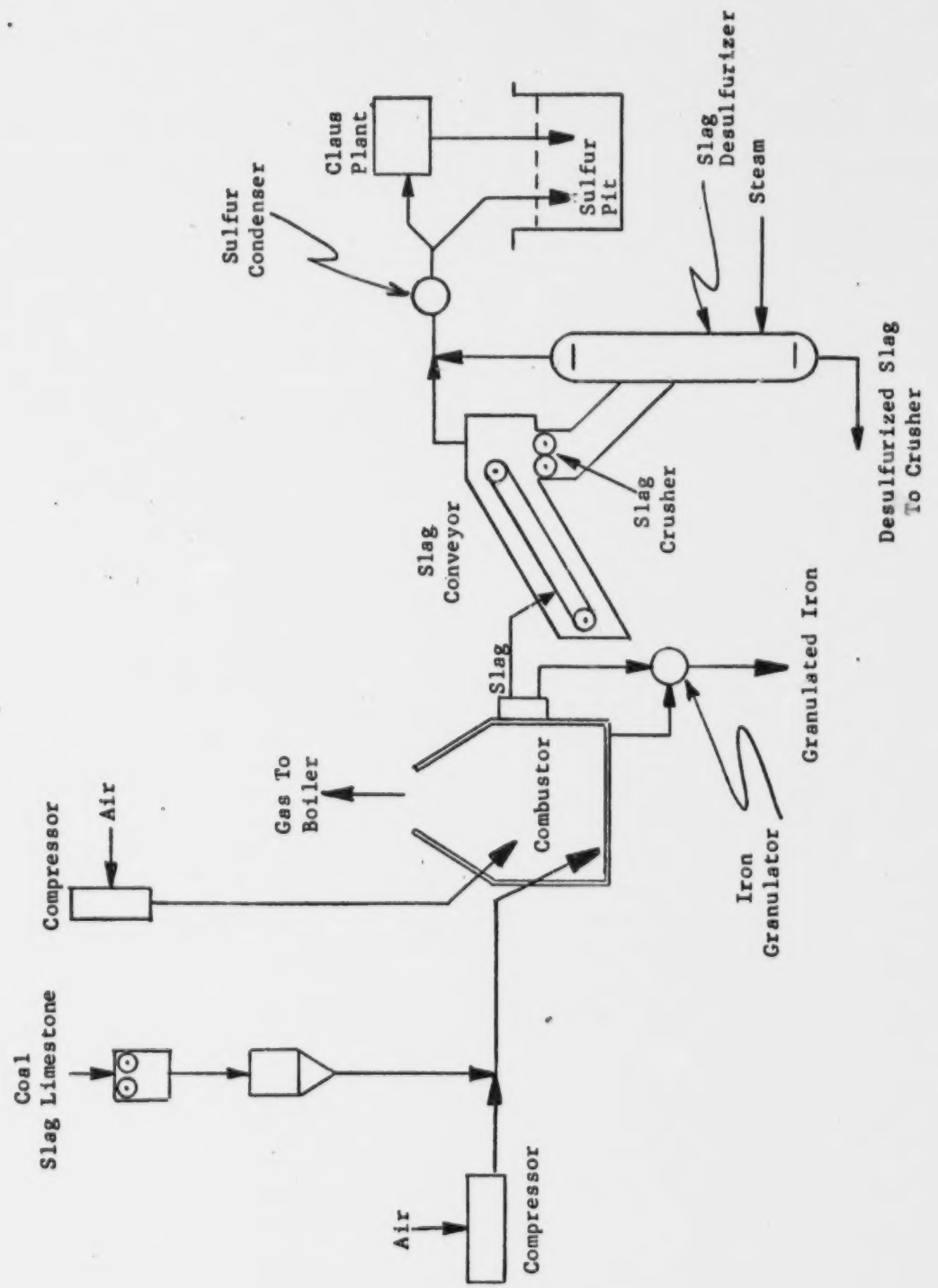

FIGURE 2--TWO-STAGE COAL COMBUSTION PROCESS

conveying of coal is supplied by separate compressors, because the large volume of combustion air is required at a lower pressure (5 psig). The carbon-monoxide-rich offgas generated in the combustor by the combustion of coal enters the boiler where it is oxidized to carbon dioxide by secondary air to produce steam for subsequent power generation.

The sulfur bearing slag formed in the combustor is separated from the molten iron and transported to the desulfurizer, via enclosed metal conveyors. Prior to entering the slag desulfurizer, the slag is crushed. In the slag desulfurizer, the sulfur-bearing slag is contacted with steam to produce a sulfur-rich gas which proceeds to a sulfur condenser and Claus unit where the sulfur is removed from the gas and deposited into pits. Part of the desulfurized slag is sent to the combustor for reuse and the rest is sold as road aggregate.

Because coal contains iron (mainly as pyrite) some iron is produced in the combustor. Iron is periodically removed from the combustor and sent to a granulator where it is contacted with a water spray to produce salable granulated iron.

EXPERIMENTAL PROGRAM

Purpose

Although most parts of the Two-Stage Coal Combustion Process are commercially used in steelmaking practice, the combination of this technology applied to the sulfur dioxide elimination problem is unique. Consequently, an experimental program was undertaken under Office of Air Programs sponsorship to study the application of a molten iron bath as a coal gasifier for conventional power plant boilers (Contract No. CPA 70-146).

To define the technical and economic feasibility of the process, it was necessary to provide answers to the following questions:

1. What combustor depth and cross-sectional area is required for a given power plant size?

   In particular, it is necessary to determine how deep into the metal bath each type and size of coal must be injected to insure that it dissolves. It should be noted that any part of the coal that does not dissolve will be carried with the offgas and probably burn to produce sulfur-bearing gases. It is, therefore, important to completely dissolve the coal in the iron bath. Obviously, some coal losses can be sustained without upsetting air pollution code requirements. With regard to the oxidation of the dissolved carbon, it is necessary to determine the optimum point of release of the air that oxidizes the carbon. Optimization is a matter of trade-off between the compression cost associated with injection of air deep into the metal bath and the loss of air utilization efficiency when the air is injected without intimate contact with the iron. Further, because of the large amount of gas generated by carbon oxidation, it is necessary to establish experimentally the allowable metal and slag turbulence (a function of gas velocity) in order to determine the combustor cross-sectional area requirement.

2. How clean is the gas produced in the combustor?

   It is necessary to determine the operating techniques that will eliminate, or at least minimize, the sulfur dioxide and particulate matter content of the gas produced. It is also desirable to

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determine to what extent two stage coal combustion minimizes the formation of nitrogen oxides.

3. Are there any combustor materials or design problems?

   If the combustor is to operate like other power plant equipment over prolonged periods, approximating one year between maintenance shutdowns, it is necessary to establish experimentally that refractory wear will not present a serious problem. It is also necessary to show that reliable and safe means of injecting coal into the iron bath can be successfully designed.

4. What slag composition should be used in the combustor?

   Since limestone must be added to the combustor to flux the coal ash and react with dissolved iron sulfur, process economics are favored by minimizing the quantity of slag and the lime content of the slag. Experimental data are needed to determine slag quantity and composition that are consistent with (1) a high sulfur retention capacity, (2) slag fluidity that is sufficient to permit continuous removal of slag from the combustor, (3) a minimum slag reactivity with commercially available refractory, and (4) amenability to slag desulfurization.

5. How can sulfur be best recovered from the slag?

   Previous research projects (EPA Contract No. 14-12-529 and No. 14-12-929) have shown that sulfur is readily recoverable from slag by reacting the slag with steam at elevated temperatures. However, the rate of reaction depends on the physical properties of the slag. Since the physical properties of the slag depend on composition, kinetic data are required on the desulfurization of slags of the composition contemplated for the Two-Stage Coal Combustion Process.

Method

The experimental program consisted of coal gasification-combustion studies in a combustor containing up to three tons of molten iron, bench-scale studies of slag properties and sulfur recovery kinetics and a study of the offgas composition as a function of coal sulfur

content. An engineering evaluation of the technical and economic aspects of the process was also made. No bench scale studies were made of the coal solubility and gasification reactions which occur in the combustor. It was felt that the 28-inch diameter, three-ton electric furnace used was the smallest vessel in which these reactions could be studied without excessive freezing of the iron and slag, which would obscure the effect of the parameters under study. In retrospect, it appears that even the large electric furnace used was somewhat small for the purpose. The details for the experimental work are described in the Appendix (presented in a separate volume).

While the combustor was being designed and installed, bench scale laboratory studies of the physical-chemical characteristics of slags which may be encountered in the combustor were carried out to provide guidance for the combustor experiments. The most important aspects of slag characterization were concerned with the search for slag compositions that would be generated by adding limestone in the combustor to flux the silica and alumina from coal ash and to react with the sulfur to produce calcium sulfide. Compositions of such slags were explored to determine what lime content would be required to produce slags that would be fluid at combustor operating temperatures and would contain sufficient free lime to provide a driving force for sulfur transfer from the iron to the slag. In addition, studies were made of such slag properties as heat capacity and crushing energy requirements. These studies were followed by studies on slag granulation and slag desulfurization, which were continued to parallel the combustor operations.

Experimental data have been obtained on a combustor capable of gasifying coal at a rate equivalent to supplying the energy requirement for a 2 megawatt power plant. An induction melting furnace was selected as the combustor vessel because it is a convenient means of preparing a molten iron bath and maintaining it at a specified operating temperature. Experimentation was divided into alternate carburization and decarburization runs. That is, coal was injected into a molten iron bath (2600-2800°F) to bring the carbon level to about 3 to 4 percent and then the bath was decarburized back to a carbon level of about 2 to 3 percent. During experimentation, a continuous offgas sampling system was used to monitor the SO_2, NO_2, NO, H_2, CO, O_2, and CO_2 content of the offgas. Bomb gas samples were also taken and analyzed in a gas chromatograph to confirm the continuous analysis and to detect nitrogen in the gas. A detailed description of experimental equipment and procedures is presented in the Appendix.

The primary experimental objectives were to determine, under various experimental conditions:

1. Carburization and decarburization rates.

2. Carburization efficiency or the fraction of the coal fixed carbon which actually increases the carbon level of the iron bath.

3. Decarburization efficiency, or the extent to which all the oxygen in the air is reacted with the carbon dissolved in the molten iron.

4. SO_2 content of the offgas during carburization-decarburization.

5. The sulfur partition ratio, defined as the ratio of the percent sulfur in the slag to the percent sulfur in the iron.

DISCUSSION OF RESULTS

This section presents a summary of the results of the experimental study on the Two-Stage Coal Combustion Process. The results are discussed by subject of study, such as slag characterization, carburization, and decarburization of molten iron. Stress is placed on the significance of these results on the design and economics of the Two-Stage Coal Combustion Process.

Slag Characterization

The search for suitable combustor slag compositions (slags that would be fluid in the combustor and would be capable of removing sulfur from the iron) is described in detail in the Appendix. The results of this search show that slags with good fluidity and high affinity for sulfur can be produced with very little excess lime--in the order of 10 to 15 percent of the slag weight. A slag composition that was used extensively in the combustor consisted of:

22 percent alumina
45 percent silica
13 percent lime, and
20 percent calcium sulfide.

This slag was used on the basis of bench-scale results that show that it has adequate fluidity (viscosity of approximately 50 poise at 2700°F). This slag also showed strong affinity for sulfur in bench-scale studies, with an equilibrium sulfur partition ratio of 20 (ratio of percent sulfur in the slag to percent sulfur in iron in contact with the slag).

Carburization

Early in the experimental work, it was established that the solution rate of carbon in the iron bath is a function of the carbon content of the bath. Figure 3 shows how the carbon solubility decreases as the carbon content of the iron increases and approaches the 5 percent saturation level. The linear relationship between the rate of solution and the carbon content of the iron suggests a carbon diffusion situation represented by the equation:

$$\frac{dC_t}{dt} \quad \frac{ka(C_s-C_t)}{v}$$

where C_t = carbon concentration in iron at time t
C_s = carbon concentration at saturation
k = mass transfer coefficient
a = particle surface area
v = volume of metal bath

The data of Figure 3 were gathered by injection of a carbonaceous material (graphite) under various conditions. The differences in the slope of the lines in Figure 3 are caused by variations in the operating parameters, such as graphite feed rate, pneumatic transport gas flow rate,

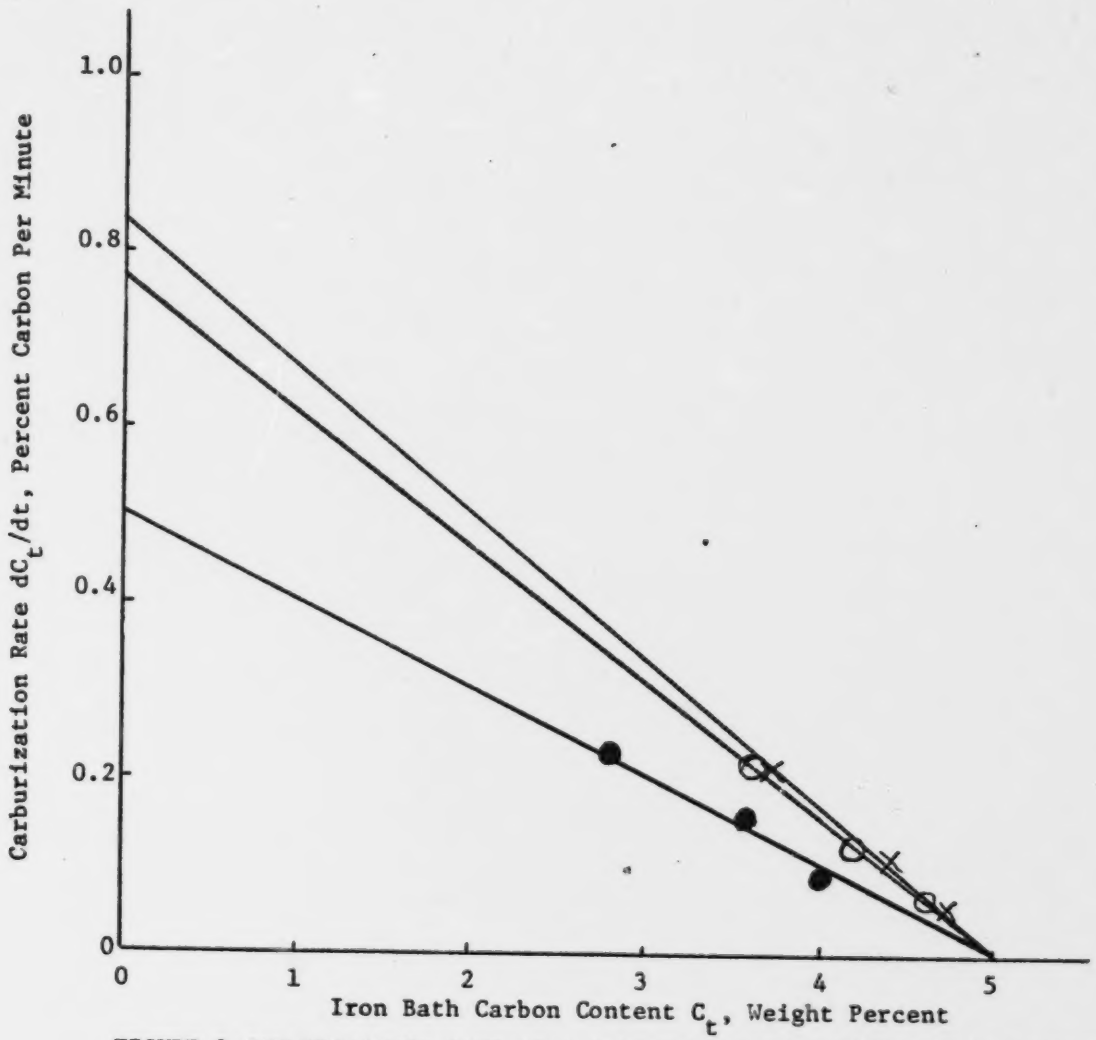

FIGURE 3-CARBURIZATION RATE AS A FUNCTION OF IRON BATH CARBON CONTENT

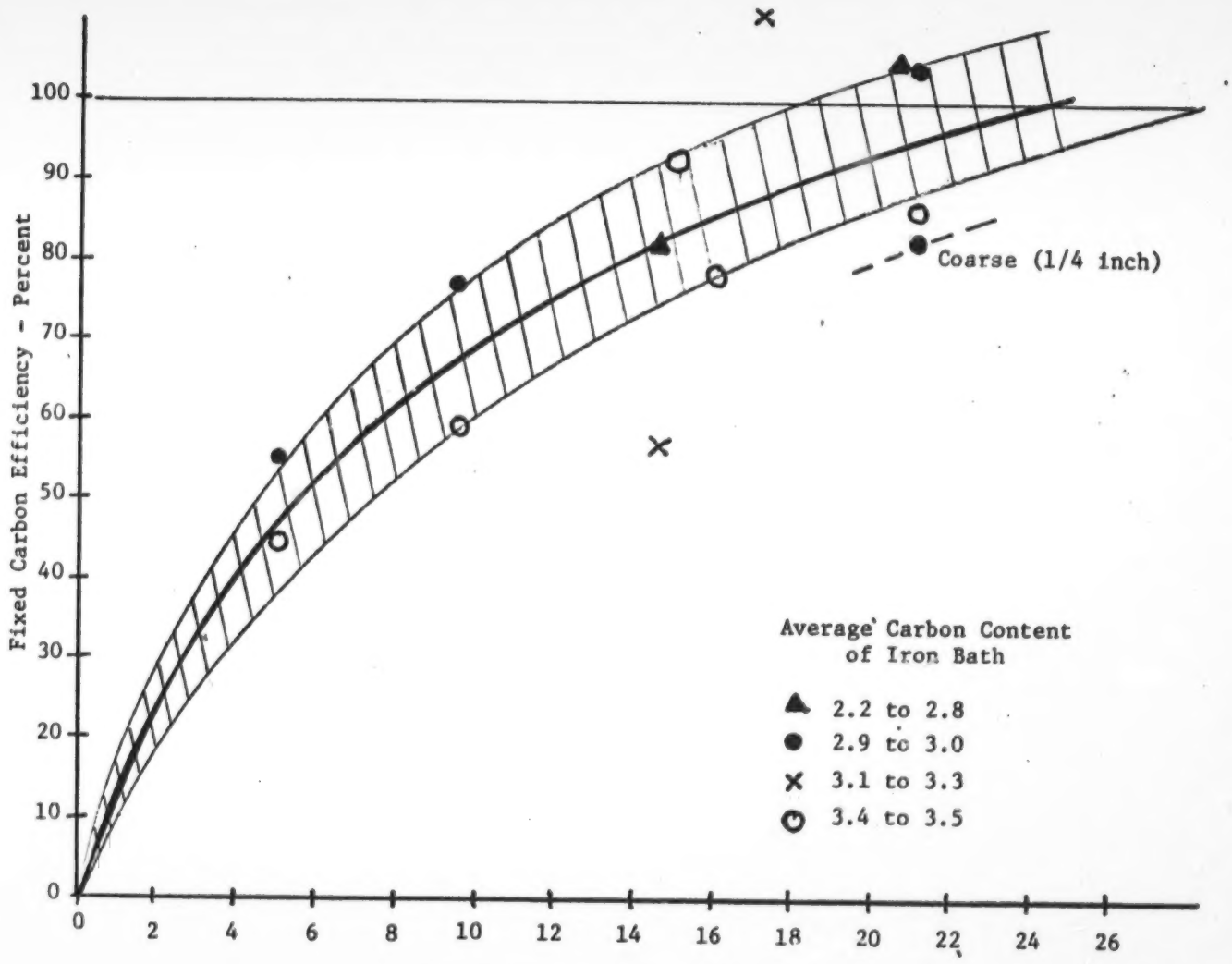

FIGURE 4-EFFECT OF LANCE POSITION ON COAL SOLUBILITY

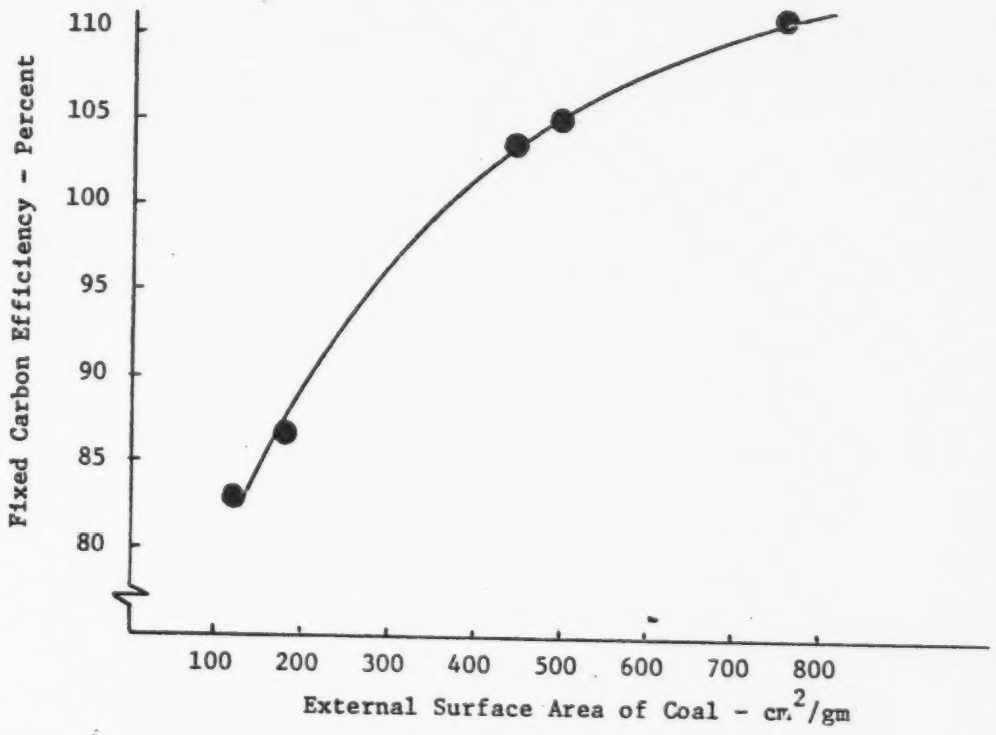

FIGURE 5-EFFECT OF COAL SURFACE AREA ON SCLUBILITY

and depth of graphite injection. All these variables affect the total particle surface area that is present in the metal bath at any given time ("a" in the above equation).

Efforts are continuing to quantify the effect of these variables in order to normalize the data in a single plot of solution rate vs. concentration. When this is accomplished, the strong effect of carbon content will be accounted for, and other variables can be studied more precisely. Until that time, data will be treated by grouping them according to iron bath carbon content.

This approach was taken in a study to determine how deep under the iron surface the coal must be injected to insure complete solution. Figure 4 shows the effect of lance position on fixed carbon efficiency. The latter quantity is the ratio of the weight of carbon dissolved in the iron to the weight of fixed carbon added with the coal. Only the fixed carbon is considered, because most of the volatile matter carbon is cracked to lighter constituents, carbon and hydrogen, and bubbles through the iron too rapidly to dissolve. However, some of the volatile matter cracked to carbon does dissolve and yields efficiencies (Figure 4) in excess of 100 percent. Figure 4 also is in essential agreement with the previously discussed effect of iron bath carbon content on coal solubility rate. As seen, the carbon efficiency tends to be higher at a lower iron bath carbon content, when the lance position is constant.

One data point on Figure 4 marked "coarse", corresponds to a lower efficiency because the coarser coal had a lower external surface area through which the carbon could diffuse into the iron. The effect is shown clearer in Figure 5 in which the fixed carbon efficiency is plotted as a function of the external surface area of three different size fractions of the same coal. All data points were obtained by injection of coal at the same depth (21 inches) and at approximately the same iron bath carbon content (3.05 to 3.37 percent). It should be noted that the surface area of the coal changes drastically after injection into the molten iron bath. Although it is not possible to measure these changes, it is reasonable to assume that the rapid evolution of volatile matter causes the coal particles to expand and assume a structure similar to popcorn, as happens during the processing of coal char. Figure 5 indicates that the surface areas of the coals tested maintained their relative ranking after injection into the molten iron.

Decarburization

In pneumatic oxygen steelmaking processes such as the basic oxygen furnace, Kaldo furnace, or the Rotor furnace[1], decarburization of pig iron to produce steel is directly proportional to the rate at which oxygen is injected into the molten metal bath. In particular, for those processes (Kaldo, Rotor) where mechanical as well as gas agitation

are employed, the rate of decarburization is a linear function of time. For example, in the Kaldo process, constant decarburization rates of about 0.2 percent carbon per minute are realized over a metal bath carbon composition of 3.6 to 1.6 percent carbon. In the basic oxygen process which relies solely on pneumatic stirring (and, consequently, does not have the agitation associated with the other processes) essentially constant decarburization rates are achieved over a narrower range of iron carbon content. Thus, commercial steelmaking process data show that the decarburization rate is controlled by the gas phase mass transfer of oxygen to the liquid metal bath. Oxygen utilization efficiencies for such processes are in the range of 90 to 95 percent. Assuming that the chemical reaction between dissolved carbon and incoming oxygen is rapid, a simple material balance relating the change in percent carbon per unit time in the metal bath is given by

$$W\frac{dc}{dt} = -kE(P)V$$

where W = weight of iron
c = percent carbon content of the molten iron
t = time
k = mass transfer coefficient
V = air injection rate
E(P) = efficiency of oxygen utilization as a function of injection lance depth and other parameters

This equation simply states that the depletion of carbon in the metal bath is solely a function of the injection air rate. The efficiency E(P) is a function of a number of variables including the gas velocity leaving the lance, the immersion depth of the lance into the metal, the ratio of lance diameter to molten bath diameter and the ratio of lance immersion depth to the total molten iron bath height. Theoretical correlations are not available to estimate the effect of these variables on the mass transfer coefficient and the interfacial area generated by the kinetic energy of the gases impinging on the molten metal. However, it is possible to determine the functional dependence experimentally. As will be shown later, for the experimentation conducted in this work, the efficiency of oxygen utilization for the combustion of carbon is related primarily to the immersion depth of the lance.

Because of the rapidity of the combustion reaction for converting dissolved carbon to carbon monoxide, the mathematical interpretation presents the simple conclusion that the decarburization rate is equal to the rate at which oxygen is made available to the molten bath. Obviously, for a constant oxygen transfer, the decarburization rate will be constant and the carbon content of the metal bath will decrease linearly with time.

A series of experiments were completed to determine the relationship between decarburization rate and oxygen utilization efficiency and the

following variables: iron bath weight, lance immersion, air injection rate, ratio of lance immersion depth to metal bath height, and velocity of injection gas leaving the lance. The weight of the iron bath was varied between 2,000 and 5,000 lbs., air flow rate from 70 to 250 SCFM, and lance position from a high of about 4 inches above the metal surface to an immersion depth of 19 inches. Substantial scatter in the data exists and obscured the effect of minor variables. However, the oxygen utilization efficiency did correlate well with the lance immersion depth. The results of this work are presented in Figure 6.

As can be seen in Figure 6, the lance position relative to the slag metal interface profoundly influences oxygen utilization efficiency. When the position of the air injection lance tip is about 4 inches above the surface of the molten iron bath, oxygen utilization is about 25 percent. When the lance tip is at the metal bath surface, the oxygen utilization is attributed solely to the creation of interfacial area between the gas and the molten iron generated by the air leaving the lance. Obviously as the tip of the lance approaches closer to the iron bath surface, the gas more efficiently creates interfacial area between the air and the molten iron to bring about a higher mass transfer rate of oxygen. When the lance is immersed into the molten iron at a depth of about 4 to 5 inches, oxygen utilization efficiency approaches 100 percent. Any further increase in immersion depth has no further effect upon efficiency and only results in a higher pressure drop requirement to overcome the ferrostatic head. Since the objective of the experimentation was to define or evaluate expected operation for a commercial vessel, the bulk of the experimental work was confined to lance submersion depth of less than 6 inches. In this way, compression cost for the injection of combustion air would be kept minimial.

As is evident from Figure 6, considerable data scatter exists for oxygen utilization efficiency. For example at an immersion depth of about 4 inches the measured efficiency varied from a low of 93 percent to a high of 108 percent. The variation in this result is attributed to the splashing that occurs within the vessel. It has been estimated that splashing can deposit about 100 to 200 pounds of iron on the walls of the vessel. For a three percent carbon melt containing 3,000 pounds of iron, this can introduce an error of about 3 to 6 percent in the efficiency calculation. Inasmuch as the oxygen utilization efficiency is calculated from the bath weight and the difference in carbon content of the molten iron at the beginning and end of an experiment, the unknown amount of splashing gives rise to errors of this magnitude.

It is of interest to point out an implied effect of lance immersion depth and bath weight on oxygen utilization efficiency. In an effort to achieve high decarburization rates, shallow molten iron bath (2,000 lbs, 15 inches deep) and high air injection rates (200 SCFM) were used. When the lance was immersed to the full depth of the iron bath, considerable splashing and lifting of the molten iron were observed. This gave rise to a low oxygen utilization efficiency as illustrated in Figure 6. This test suggests that a deep immersion depth in a shallow

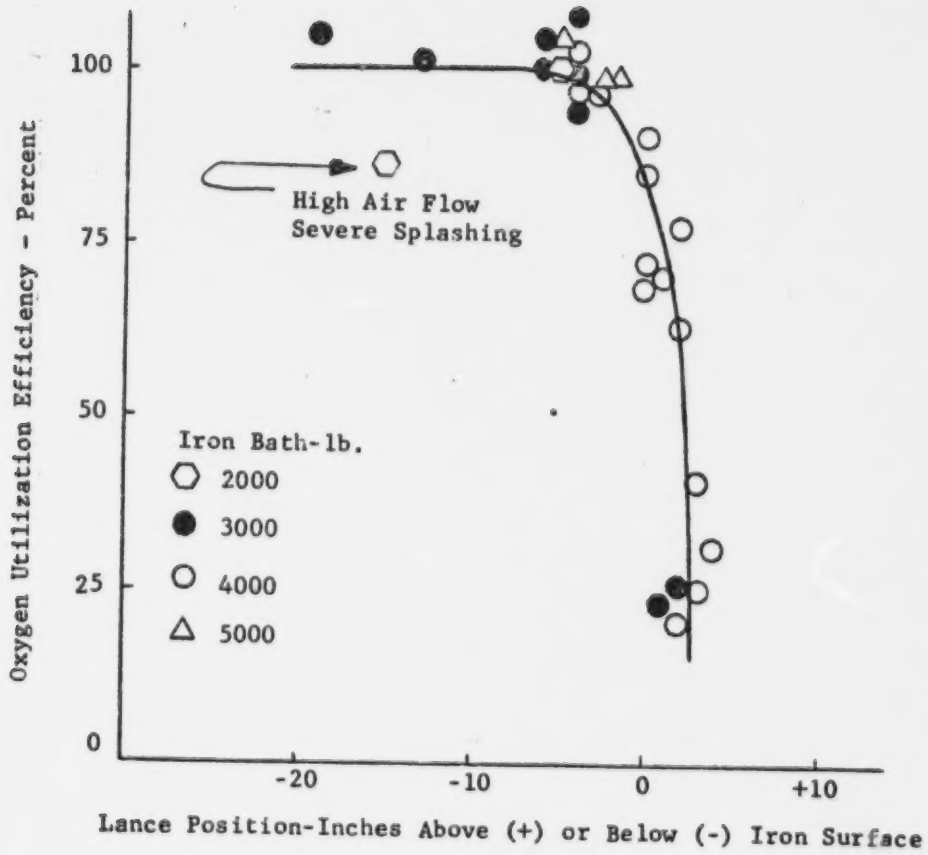

FIGURE 6-EFFECT OF LANCE POSITION ON OXYGEN UTILIZATION

bath (and for the geometry of the system used in this work) considerable bed eruption can occur to lower oxygen utilization efficiency. However, the latter observation has little commercial interest and is discussed only to explain experimental results. Inasmuch as a commercial combustor will operate at minimum air injection depth commensurate with high oxygen utilization efficiencies to keep compression costs down, lance submersion depth will be maintained at about 5 inches and bath eruption will not occur.

The data exhibited too much scatter to correlate decarburization efficiency with gas velocity at constant lance immersion depth. Nevertheless, it is believed that such an effect should prove to be substantial. For example in a basic oxygen furnace (BOF), oxygen injection is carried out at supersonic lance tip velocities. Normally, the lance is located several feet above the surface of the molten iron. Even so, at these high velocities, sufficient oxygen transfer exists to generate oxygen utilization efficiencies of about 90 to 95 percent.

To determine the effect of carbon concentration on decarburization rates, a number of experiments were completed in which molten iron baths of varying carbon content and weight were decarburized at different flow rates. Typical data for the variation of hot metal carbon content with air injection time are presented in Figure 7. The data show that the decarburization rate is a constant and that the percent carbon in the molten iron varies lineraly with time. This tends to support the conclusion that the decarburization rate is independent of carbon ceontent and is primarily a function of the transfer of oxygen from the gas phase to the liquid metal.

If the oxygen transfer were 100 percent efficient, the slopes of each of the decarburization curves would be directly proportional to the air input rate. Because of inefficiencies generated by lance position and other variables, not all of the data are amenable to this simple translation. However, by incorporating into the rate equation, the efficiency of oxygen utilization correlation presented earlier, it is possible to normalize all the rate data so that the decarburization rate can be presented as a simple function of efficiency, air injection rate, and bath metal weight. The normalized data are presented in Figure 8. As expected, the data show a high degree of correlation and indicate that the decarburization rate increases with increasing air injection rate and decreasing metal bath weight.

Because of the limitations of the experimental combustor (i.e., small size), high decarburization rates were obtained when the combustor contained the least amount of metal. This is to be expected since, for a given air flow rate, high decarburization rates are achieved by decreasing the amount of metal contained within the combustor. However, for the same geometrical reasons, these data tend to exhibit the

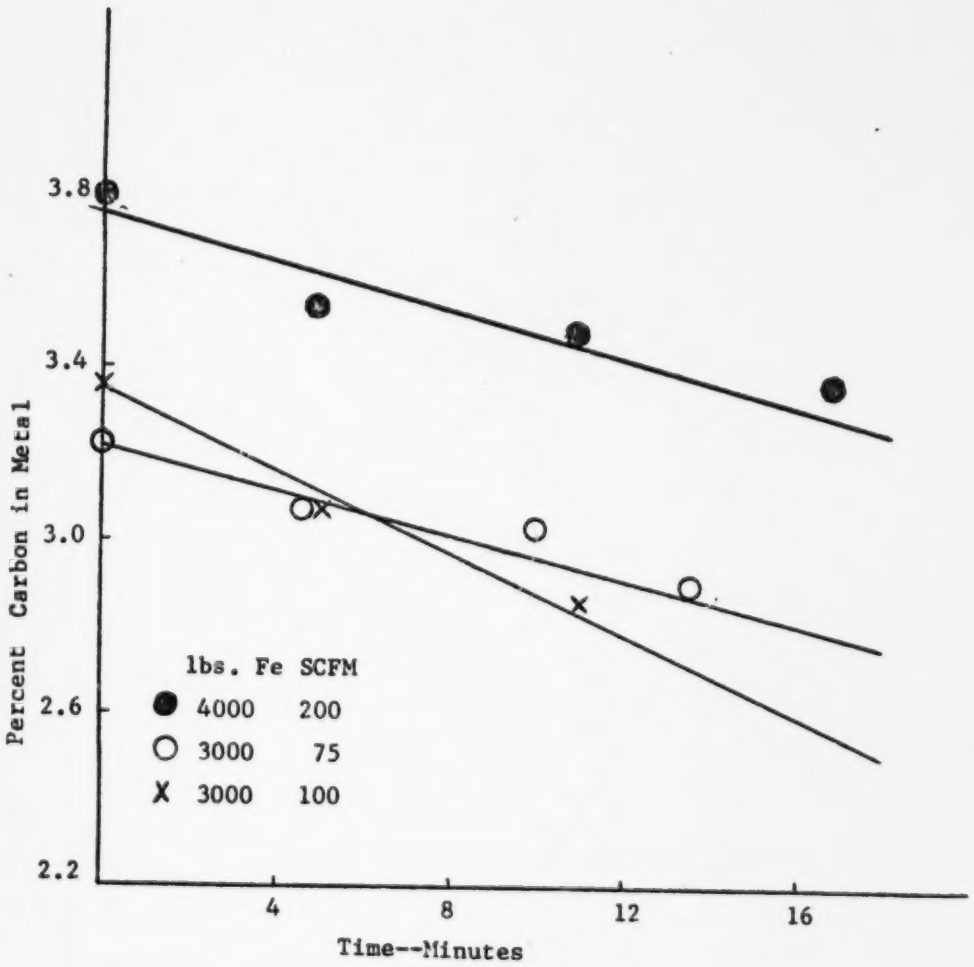

FIGURE 7-VARIATION OF METAL CARBON CONTENT WITH AIR INJECTION TIME

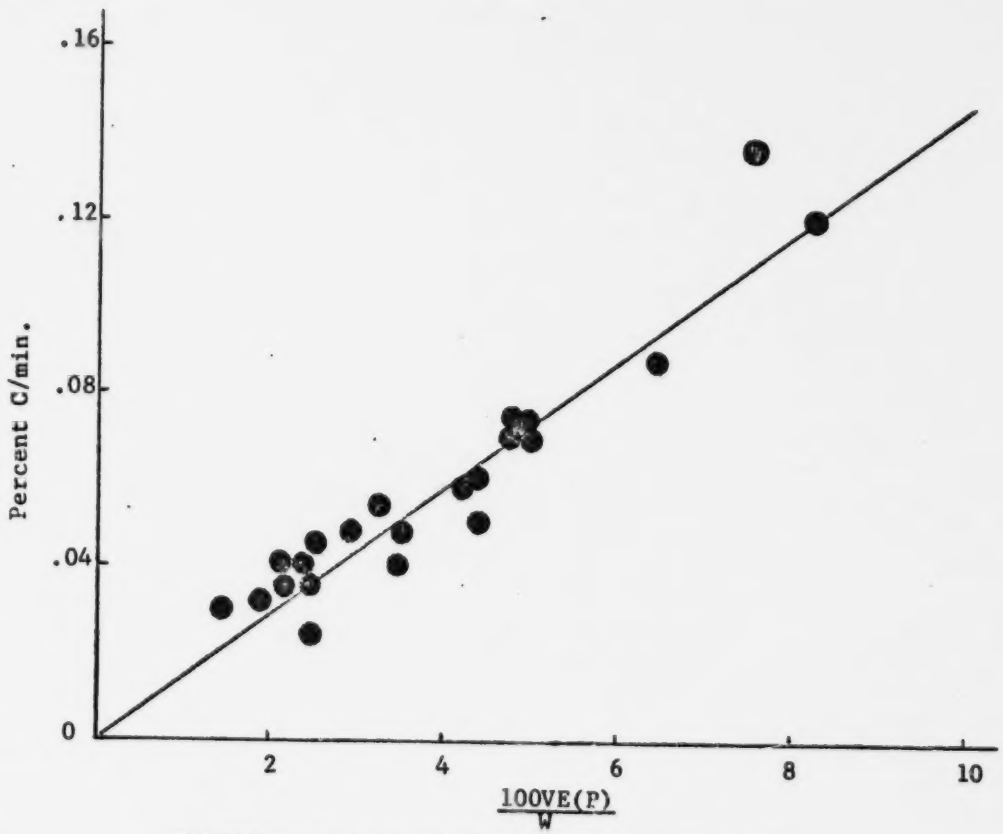

FIGURE 8-DECARBURIZATION RATE AS A FUNCTION OF OPERATING VARIABLES

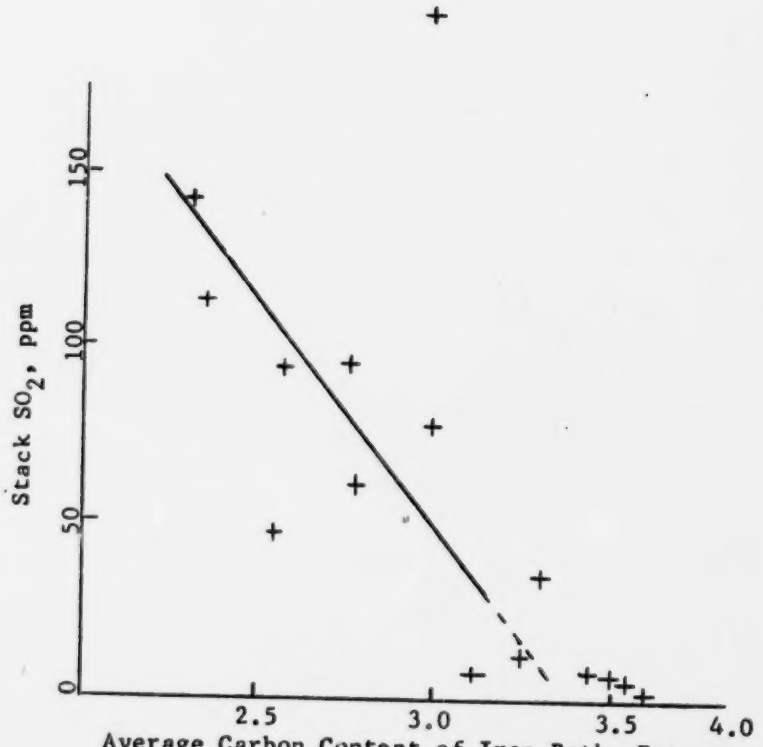

FIGURE 9--EFFECT OF BATH CARBON ON SO_2 EMISSION

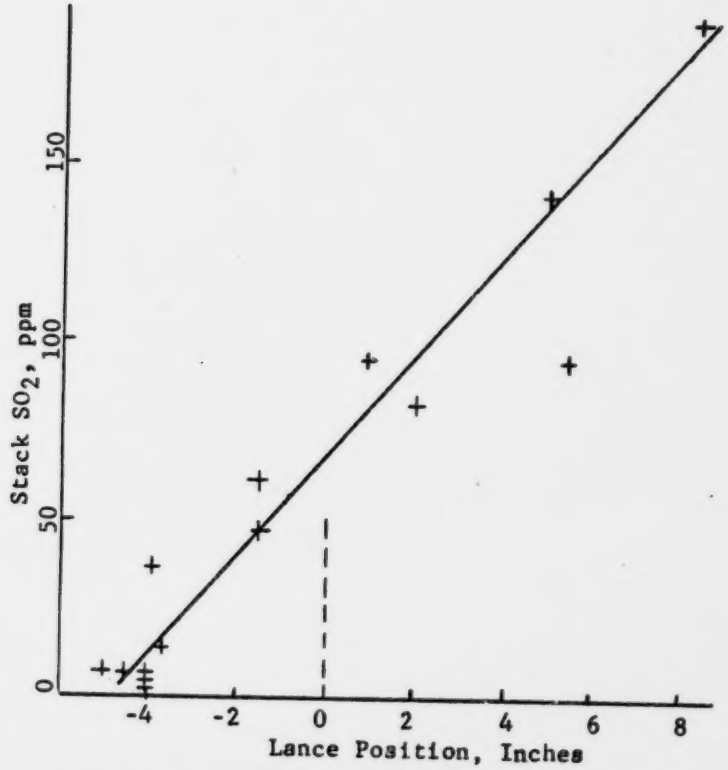

FIGURE 10--EFFECT OF LANCE POSITION ON SO_2 EMISSION

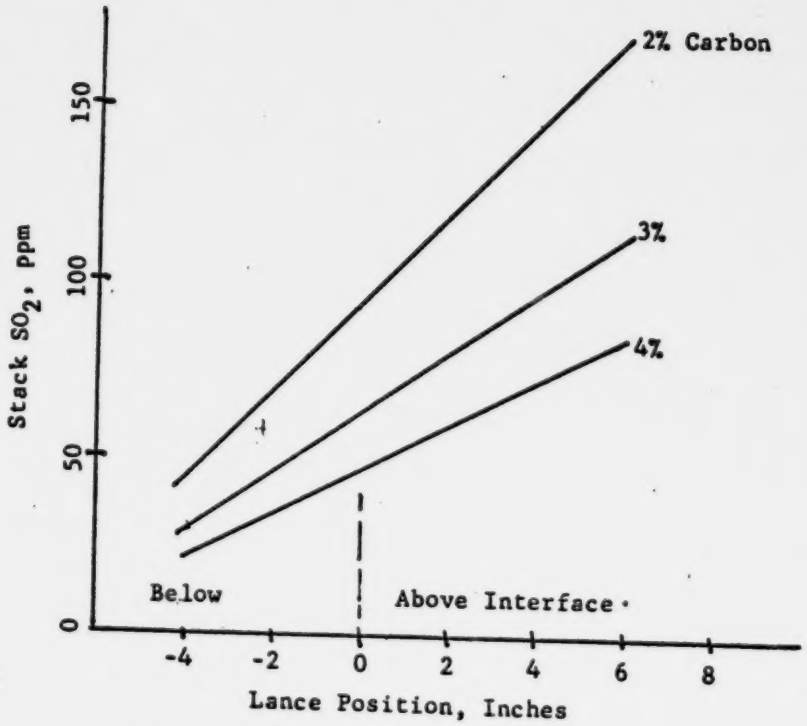

FIGURE-11-EFFECT OF IRON BATH CARBON CONTENT AND LANCE POSITION ON SO_2 EMISSION

greatest amount of scatter as shown on Figure 8. Physical size alone limits the amount of air that it is possible to inject within the experimental combustor. It is of interest to point out that commercial Bessemer converters readily obtain decarburization rates of 0.25 percent carbon per minute and higher[2]. Consequently, we believe that commercially acceptable decarburization rates not only have been demonstrated in the samll experimental unit but are supported by data available on a commercial scale from the steel industry.

SO_2, NO and Particulate Emissions

The SO_2 content of the combustor offgas is determined continuously during all data runs. This value is averaged over each run and converted to an equivalent stack SO_2 content which would result in a commercial power plant burning the combustor offgas in a boiler. Figure 9 shows a plot of the equivalent stack gas SO_2 content during decarburization. These results are for experiments performed under various experimental conditions. Consequently, there is much scatter but the trend is obvious. The SO_2 content of the stack offgas decreases as the carbon content of the iron increases. One factor of particular commercial importance should be stressed. The data show that SO_2 levels of 50 ppm or less can be achieved by maintaining a minimum three percent carbon level in the combustor. It is expected that in commercial use, the combustor will operate at a carbon level between three and four percent.

A prime operating variable affecting SO_2 generation is the position of the lance relative to the slag-metal interface. The lower the lance is into the metal, the higher will be the decarburization efficiency and less unused oxygen will be available to form sulfur dioxide by reaction with the CaS content of the slag. This is shown in Figure 10 which is a plot of the equivalent stack gas SO_2 content *vs.* lance position during decarburization. As seen, the SO_2 content decreases from about 200 ppm with the lance in the slag (nine inches above the slag-metal interface) to about twelve ppm with the lance in the iron, four inches below the slag-metal interface. The results of Figure 10 include experiments in which the carbon content of the iron varied between 2.5 and 3.75 percent carbon content. Since both carbon level in the molten iron and lance position affect SO_2 production, the SO_2 emission data were correlated with regard to both variables. Figure 11 presents the smoothed data obtained from cross-correlation of these variables. The data scattered somewhat, but conservative relationships are presented. This generalized plot shows that SO_2 emission decreases with increasing carbon content and increasing lance immersion depth. This means that in a commercial combustor operating at 3 to 4 percent carbon with a lance immersion depth of 4 inches into the iron, less than 50 ppm SO_2 will be found in the stack gas.

The concentration of NO and NO_2 in the combustor offgas was also measured continuously and averaged for each run. In general, the concentration of these gases remained below 50 ppm. These low levels of nitrogen oxides (NO_x) are to be expected in the combustor's reducing atmosphere. However, it must be pointed out the secondary combustion of the combustor offgas in a boiler will occur under oxidizing conditions, and additional NO_x formation is to be expected. The NO_x generation in the boiler will depend on flame temperatures, excess air used, and residence time in the boiler. It remains to be seen whether new boilers can be designed and existing boilers can be modified to take advantage of the gaseous fuels generated by the process to operate at reduced temperatures, lower excess air, and at decreased residence time.

Particulate emissions from a combustor operating at steady state can be (1) undissolved coal particles that escape from the iron bath if the coal is not injected deep enough, (2) iron oxide fume generated if the carbon level in the bath should drop below 1.5 percent instead of the 3 to 4 percent design carbon level, and (3) iron and slag particles which splashed out of the bath and are carried out of the combustor by high velocity gases. The first two causes of particulate emissions can be adequately controlled as discussed in conjunction with the results of carburization and decarburization. That is, by injecting the coal sufficiently deep, undissolved coal leaving the system is minimized; and by using iron carbon levels of 3 to 4 percent, carbon will be preferentially oxidized, thereby, minimizing iron oxide formation and carryover. However, reducing gas velocities to minimize particulate carryover in the combustor offgas can affect economics of the process as well as its practical application in existing plants by causing the combustor area to become unwieldy.

For this reason, considerable effort has been expended in the attempt to obtain meaningful and reliable data on particulate matter carryover from the combustor. Data gathering has been hampered by the geometry of the experimental combustor which limits, of necessity, the free-board of the metal bath and by the intermittent method of operation. The low free-board height permitted rather heavy coal particles to be carried out of the combustor and deposited on horizontal piping ductwork during carburization runs, only to be picked up by the higher velocity gases created during subsequent decarburization runs. The intermittent method of operation made it difficult to obtain reasonable in-flight samples and has forced the reliance on a total dust gathering technique using a filter bag. This filter bag was located at the exit of the offgas handling facility and was allowed to gather dust over the duration of a run. The latter technique was rather recently installed and is currently undergoing refinement, primarily to minimize the weighing errors that are introduced by the large weight of the bag relative to the small weight of particulates.

TABLE 1

Typical Combustor Slag/Iron Compositions

	Slag					Iron	
	CaO	Al_2O_3	SiO_2	S	Basicity	S	Partition Ratio
With Agitation	15	30	55	5.6	0.17	0.48	11.5
	17	27	56	4.9	0.21	0.48	10.1
	16	29	55	5.0	0.19	0.48	10.4
	15	32	53	4.8	0.18	0.48	9.9
	17	28	54	4.8	0.21	0.48	9.9
Without Agitation	12	35	53	0.16	0.14	0.84	0.19
	18	36	46	0.85	0.22	0.55	1.55
	14	31	55	0.21	0.16	1.46	0.14
	15	31	54	0.21	0.18	0.40	0.53
	14	44	42	0.32	0.16	1.30	0.25

Notes:

1. CaO, SiO_2, and Al_2O_3 are on a CaS-free weight percent basis.
2. Basicity is the weight ratio $CaO/(SiO_2 + Al_2O_3)$.
3. Partition ratio is defined as the ratio of the percent sulfur in slag to percent sulfur in iron.

Combustor Slag Studies

To expedite start-up instead of waiting for slag to form from limestone additions and coal ash, combustor slags were produced by injecting a dry mixture of slag components into the bath at the onset of a test series. Laboratory studies indicated that a basicity weight ratio of CaO to SiO_2 plus Al_2O_3, of 0.2 or less would yield a fluid slag. Consequently, most experimental combustor runs were made with slag which had an initial basicity of 0.2. Carburization runs, in which coal ash migrated to the slag, lowered the basicity. In general, slag basicities were in the 0.1 to 0.2 range.

Combustor slag data generally fall in two categories; those collected when the bath was agitated, maintaining intimate contact between iron and slag, and those collected when no agitation was used. The bath was well agitated during carburization and decarburization runs. However, it is impractical to maintain bath agitation in the between-runs intervals which sometimes lasted for several hours. In the latter case, the metal stirring caused by the induction furnace provided a limited amount of agitation. A list of typical combustor slag compositions and the iron in contact with the slag is shown in Table I.

When dry slag ingredients containing about 8 percent sulfur were added to the system and with no subsequent agitation, the sulfur was retained mostly by the iron. As seen in Table I, under these conditions, the iron had up to about 1.5 percent sulfur and the slag from about 0.2 to 1 percent sulfur, yielding partition ratios of 0.2 to 1.6. These low partition ratios result because without continuous agitation, the slags tended to be cool relative to the metal--in the order of 2000°F as compared to metal at 2600°F. In fact, the slags tended to crust over on the surface and became extremely viscous because of radiant heat losses from the slag to the cooler combustor transition section. The laboratory study has shown that as the slag temperature decreases, the partition ratio also decreases. For example, the equilibrium partition ratio for a 0.2 basicity slag, decreased from about 170 at 2680°F to about 30 at 2490°F. Consequently, the low partition ratios obtained under nonagitated conditions are expected and confirm laboratory results.

To provide agitation between the slag and iron and thereby approximate a commercial operation, a small flow of nitrogen was continuously bubbled into the iron to agitate the slag during several runs. As expected, agitation resulted in increased mass transfer of the iron sulfur to the CaO-bearing slag to form CaS with a corresponding increase in slag sulfur content and decrease in iron sulfur content. Agitation also kept the slag hot at near the iron temperature and, as shown in the laboratory study, higher partition ratios result at higher operating temperatures.

With the slag and iron agitated in this manner, partition ratios in the order of 10-12 were obtained (Table I). The iron contained about 0.5 percent sulfur and the slag about 4.8 to 5.6 percent sulfur. This con-

firmed laboratory results in which partition ratios of approximately 10 to 20 were obtained for 0.1 and 0.2 basicity slags (see Appendix).

In the actual combustor operation, higher partition ratios are expected, because agitation between slag and iron will be much more pronounced than was obtained in the experimental combustor. These findings are economically significant because it is desirable to have the slag contain as much of the coal sulfur as possible. Sulfur remaining in the iron is a by-product credit loss to the process.

Combustor slags containing as much as 12 percent sulfur were prepared. However, these slags tended to be viscous and contained semi-solid slag lumps. This is expected since the laboratory study showed that increasing the CaS content of 0.2 basicity slags beyond 10 percent sulfur yielded extremely viscous slags (1000 poise).

In summary, the laboratory and experimental combustor slag studies indicate that partition ratios of at least 10 can be expected under actual combustor operating conditions.

Materials Problems

There are two main materials problems involved in combustor design and operation. The obvious problem is that of refractories for the combustor proper and the ductwork between the combustor and the boiler. Operating at temperatures in the range of 2500 to 2700°F, the combustor and ductwork will require some of the highest quality refractories available at this time, but will not require any advance of the current state of refractory art. Containment of the iron is not expected to present any difficulty, provided that coal and air injection lances are located so that coal and air impingement on the refractory bottom and sides of the combustor is minimized. In this manner, the erosion effects become insignificant. Refractory endurance with regard to containing molten iron is backed up by blast furnace experiences where hearth refractories last for several years.

The main problem is that of slag attack on refractories within the combustor. Refractory performance in the experimental combustor and steelmaking experience indicate that refractory choice should emphasize protection from slag attack. Since the experimental combustor has operated with acid slags (slags in which the ratio of lime to silica and alumina is relatively low), the combustor has been lined with acid linings consisting primarily of alumina. The study of refractory linings is not complete at this time, and quantitative data that can be extrapolated to prolonged operation of a very large combustor cannot be obtained without extremely expensive tests (which must include a study of vessel design as well as refractories). However, the experience with the current brick lining of the combustor is very encouraging. The current lining consists of a dense (porosity of 14 to 18 percent)

high alumina (90 percent Al_2O_3) bricks. This lining has been in use over four campaigns covering a total operating time of five weeks, and is still useable. In between these campaigns, the lining has been patched but the deepest penetration of slag attack on the brick has been well under two inches with the average being less than one inch. It is expected that the forthcoming refractory test will provide data of a more quantitative nature. Even if no better refractory is found as a result of the test, it is reasonable to expect that dense high-alumina brick can be used in a refractory design that will permit combustor operation in the order of one year's duration.

A materials and design problem which is now under intensive study is that of lances for the injection of coal and air under the surface of the iron in the combustor. As indicated in the preceeding discussions of carburization and decarburization, it is necessary to release the air and the coal under the surface of the iron. To accomplish this, it is necessary to develop tubes (lances) that are capable of operating continuously in contact with the molten iron and slag. Further, the coal injection lances must be cooled to prevent excessive heat transfer to the coal which would cause the coal to coke and possibly plug the lance. Because accidental release of water under the iron surface would release very large quantities of gases, creating a safety hazard, water-cooled lances are not considered desirable.

Accordingly, an experimental study is now under way to design and evaluate non-aqueous cooled submersible lance systems for both coal and air injection. Oils, molten salts, and low-melting point alloys are candidate cooling materials that can be used in conjunction with metal lances.

Slag Desulfurization Kinetics

Slag desulfurization is a heterogeneous reaction between water vapor in the gas phase and solid sulfur, presumably existing as calcium sulfide in the slag. Consequently, a number of rate-determining steps may be postulated. The desulfurization reaction rate may be controlled by the transfer of water vapor from the bulk gas phase to the slag particle, diffusion of reactant and products through the pores of the slag particle, or by chemical reaction kinetics. The latter is generally a strong function of temperature whereas the mass transfer steps show a much smaller dependence.

Although the reaction steps involved in the desulfurization of slag with water vapor are not known, it can be assumed that a simple stoichiometric relationship exists between the reactant and product species involved. Assuming that the reaction is controlled by the mass transfer of water vapor from the bulk gas phase to the slag, a simple material balance around a differential reactor can be written as:

$$\frac{w\, dC_s}{p\, dt} = c_1 k_g a y \qquad (1)$$

where w = weight of the slag
p = density of the slag
C_s = sulfur content of the slag
t = time
c_1 = stoichiometric conversion constant
k_g = mass transfer coefficient
a = slag specific surface
y = mole fraction of water in the gas phase

Equation (1) assumes that chemical kinetics are very rapid, and that the rate of sulfur removal from the slag particle is directly proportional to the mass transfer of water vapor from the gas phase to the slag particle. The mass transfer coefficient is a function of the flow characteristics in the reaction system and depends as well upon the physical properties of the gaseous constituents. In general, k_g is a function of the Reynolds Number and the Schmidt Number. The Schmidt Number, a dimensionless group of variables characterizing the physical properties of the gas, remains relatively constant for small temperature variations. Consequently, if it is assumed that the reaction proceeds over small temperature ranges, the Schmidt number will present no significant effect on the mass transfer coefficient. With this assumption, the relationship between the mass transfer coefficient and system flow parameters given in the reference can be expressed by the proportionality:

$$k_g \quad D^{-0.41} G^{0.59} \qquad (2)$$

where D = diameter of the slag particle
G = flow rate of the fluid

Substituting Equation (2) into (1), re-arranging and integrating for a constant flow system with slag particles having initial sulfur concentration C_i, the following relationship is obtained:

$$1 - \frac{C}{C_i} = C_2 a G^{0.59} y t / w C_i D^{0.41}$$

where C_2 = constant defines the sulfur level in the slag as a function of reaction time.

A detailed description and discussion of the experimental equipment and procedure can be found in the Appendix and will not be discussed here. The results of the experimental work show that the slag desulfurization

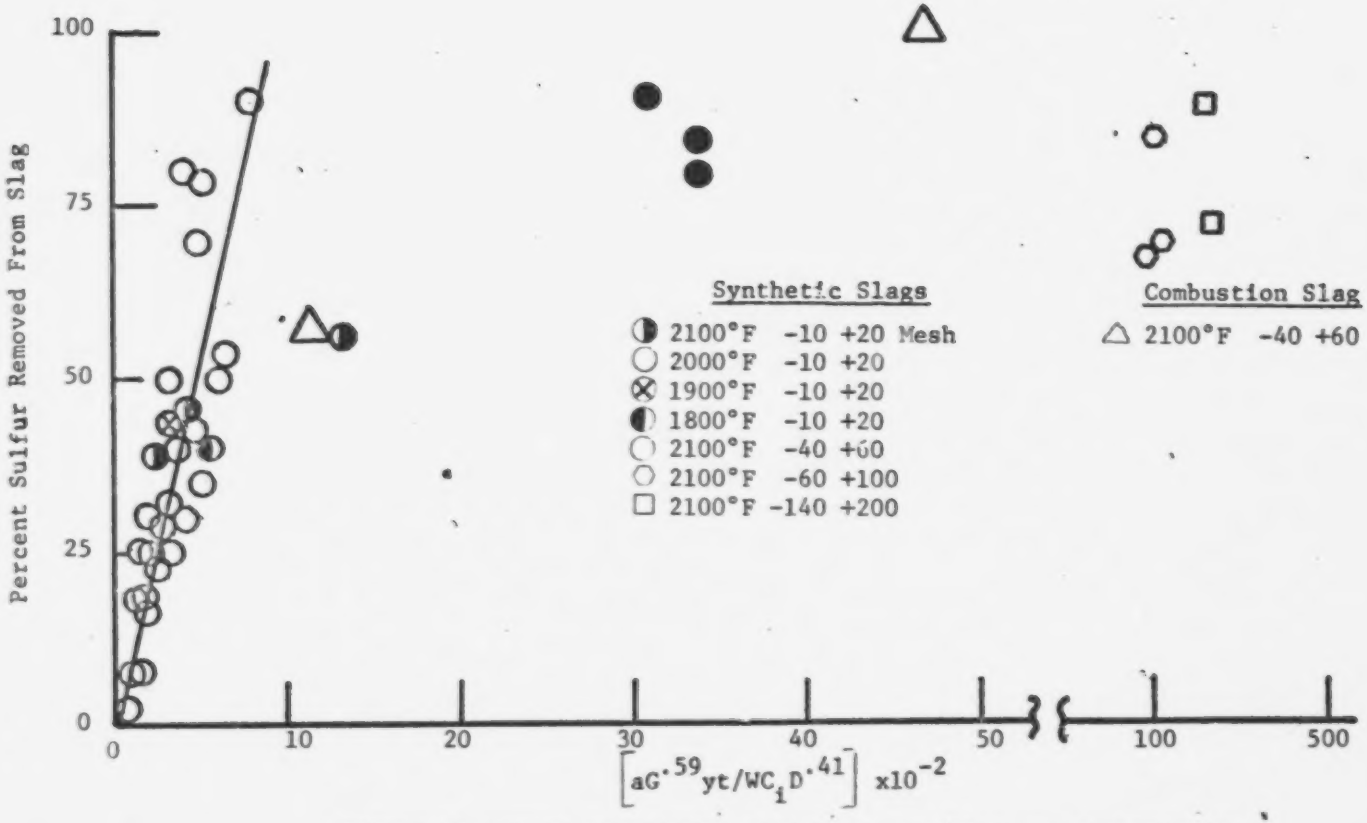

FIGURE 12-EFFECT OF PROCESS PARAMETERS ON SLAG DESULFURIZATION

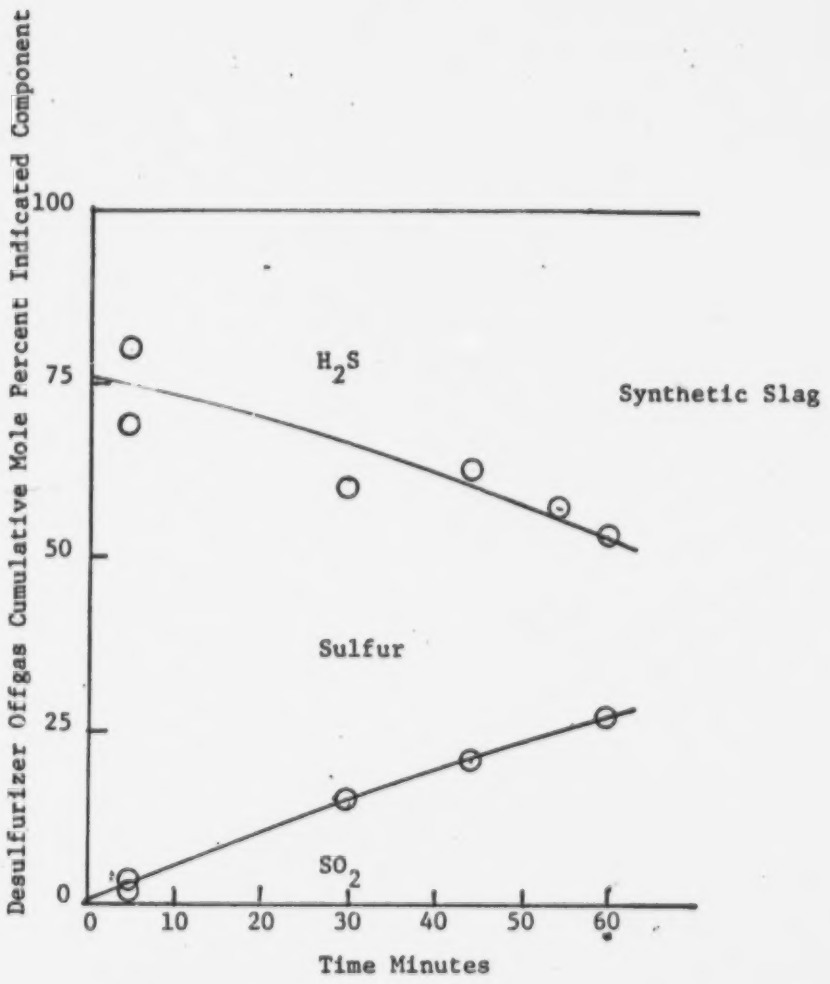

FIGURE 13-VARIATION OF OFFGAS COMPOSITION WITH TIME AT 2000°F

The offgas is a rather complicated function of water flow rate, particle size, temperature, and partial pressure of water vapor in the gas phase. The relationship between these variables is not yet understood. Nevertheless, Figure 13 is used to illustrate the general way in which hydrogen sulfide, sulfur dioxide and elemental sulfur content vary with time. In all of the experimentation conducted thus far, H_2S to SO_2 ratios have varied from a low of about 1 to a high of about 15. Elemental sulfur recovered depending upon operating conditions, varied from about 10 to 55 percent. In general, higher temperatures favor the formation of elemental sulfur and lower H_2S and SO_2 ratios. Low water input rates tend to produce high H_2S and SO_2 ratios.

The desulfurized (99 plus percent) experimental combustor slags produced an offgas whose cumulative elemental sulfur content was 53 percent and the cumulative H_2S to SO_2 ratio was 1.6 at the end of two hours.

Results thus far indicate that slag desulfurization is mass transfer controlled. Fortunately, it presents no chemical reaction kinetics limitations that would prohibit the design of reasonably sized reaction vessels. Although complete design information is not yet available, the engineering design must take into consideration tendencies for slag sintering to occur. The slag must be simultaneous desulfurized and rapidly cooled in the desulfurizer to below about 2000°F so that sintering effects will not occur. Based on the tendency for the slag particles to adhere to each other (as found in the experimental effort) it is estimated that the time at temperatures about 2000°F in the desulfurizer must be about 5 minutes or less to prevent sintering. Consequently, the design of the upper portion of the desulfurization tower will be limited by the rate at which the largest slag particle will cool to the desired temperature range at a specified time. This implies that for the production of a road aggregate material, the cooling rate will determine the largest size lump that can be produced. Since the desulfurization tower will be a continuous countercurrent moving packed bed, simultaneous heat-mass transfer considerations will govern the geometry of this system.

Obviously, design criteria should be based on the largest particle diameter to be processed through this system. It is tentatively estimated that depending upon the particle size requirement of the end product, a residence time of about 30 to 150 minutes will be required in the reactor.

COMBUSTOR DESIGN BASIS

The size of the combustor(s) required in the Two-Stage Coal Combustion Process depends on a number of process parameters such as the temperature, pressure, and composition of the offgas leaving the bath surface, and the coal composition which affects the combustion air rate requirement, the coal rate into the process, and the offgas composition. Once these factors are specified, the volumetric offgas flow rate and the coal rate are known or can be calculated.

The diameter of the combustor is controlled by one of two design criteria. The superficial offgas velocity must be below a specified value, tentatively set at 25-35 ft/sec.-based on basic oxygen furnace technology, and there must be sufficient iron in the combustor to accept coal at an attainable solubility rate. The depth of iron has been established at 3-4 feet to totally solubilize the coal. Consequently, for any given combustor diameter and set of process conditions, both the offgas velocity and coal solubility rate can be established when the volumetric flow rate of offgas, the coal rate, and carbon content of the coal have been determined.

In general, when air is used for combustion, the offgas velocity criteria will control the diameter of the combustor. Figure 14 presents a plot of combustor diameter vs. offgas velocity (2500°F) for a process consuming 361 TPH of coal to supply the energy requirements of a 1000 MW power plant. The coal has a 12,500 BTU/lb. higher heating value with the following ultimate analysis:

total carbon	- 68.1
hydrogen	- 5.0
oxygen	- 7.3
nitrogen	- 1.5
sulfur	- 3.6
ash	- 14.5

For this process case, one-60 ft. diameter combustor (2820 ft^2) will be required to yield an offgas velocity of 25 ft/sec. requiring a coal solubility rate of 0.11 percent C/min. However, to insure total reliability, three-38 ft. diameter combustors would be used. Thus, when one combustor is down, the other two would handle the full power plant load. Three-38 ft. diameter combustors would have a surface area of 3400 ft^2 and two would have a surface area of 2270 ft^2. Under a full power plant load-two combustor operation, the offgas velocity would be increased to about 31 ft/sec and the coal solubility rate would be about 0.18 percent C/min.--both values within specified design criteria.

The lances used in the process carry either an air-coal mixture, preheated combustion air, or a preheated combustion air-flux mixture, into the combustor. For the sake of this discussion, it is assumed that the total air requirement of the process flows through a number of

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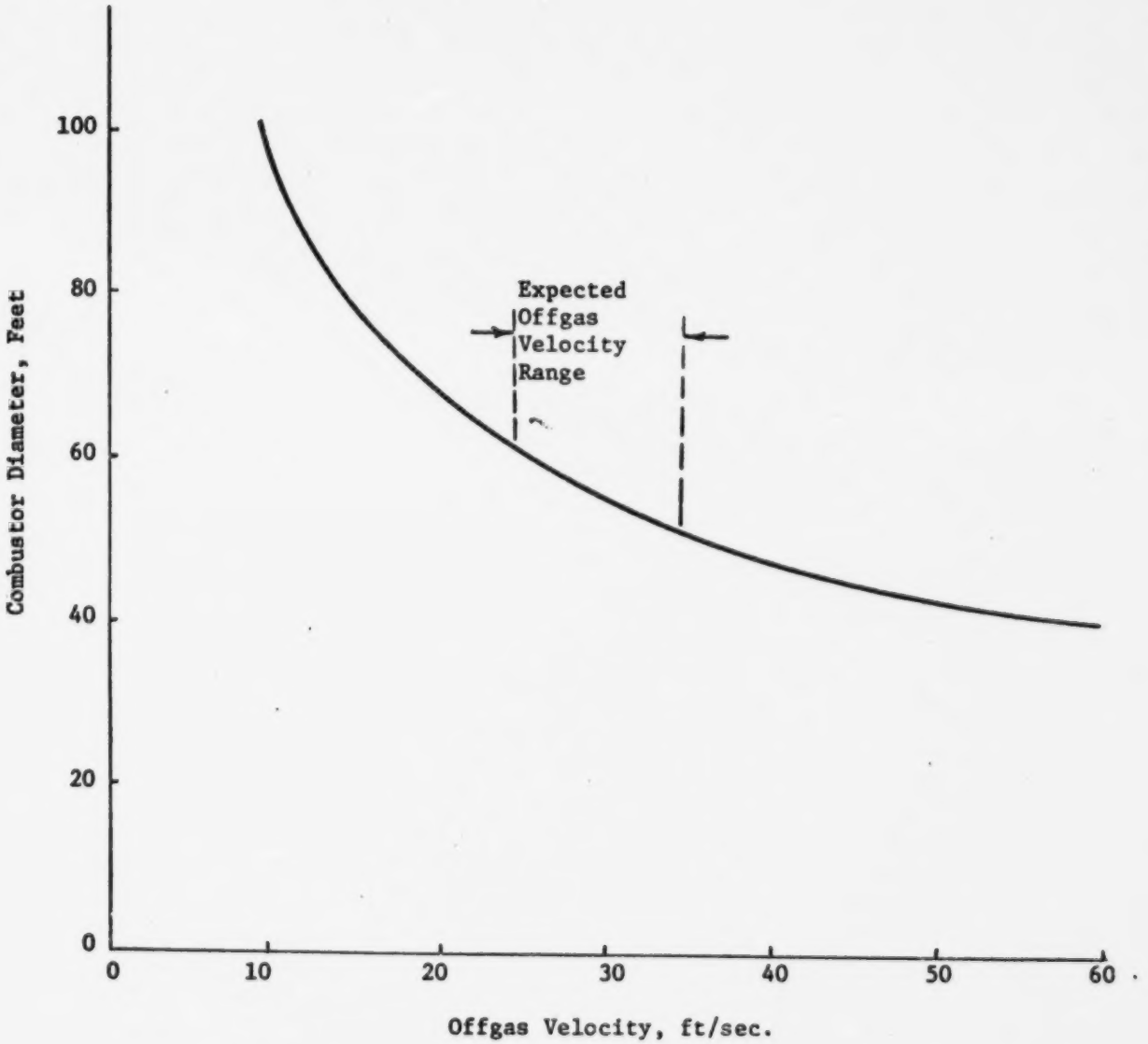

FIGURE 14-COMBUSTOR DIAMETER VERSUS OFFGAS VELOCITY

single sized lances. The 361 TPH of coal discussed above requires 1222 tons per hour of air, which is equivalent to about 1.6 MM ACFM or 26,600 ACFS. For lances designed to carry air at a rate of 200 ft/sec., a 134 ft^2 lance I.D. area is required. If 18 inch I.D. lances are used with a 1.75 ft^2 I.D. area, then 76 lances will be required--or 25 for each 38-foot diameter combustor. These lances would have an outside diameter of 30 inches (5 ft^2); therefore, for each 38 diameter combustor (1135 ft^2 area) about 125 ft^2 would be used for lances. Thus, only about 10 percent of the available bath surface is taken up by the lances. When three 38 foot diameter combustors are in operation, each will have a superficial offgas velocity of about 21 ft/sec. which would increase to about 23 ft/sec. because of the area taken up by the lances. When two of the three 38 foot diameter combustors are operating at full load, the velocity would be 31 ft/sec. which would increase to about 34 ft/sec. if the decrease in available area due to the lances is accounted for. Thus, even under the two combustor operations, all design criteria are met.

ECONOMIC EVALUATION

To evaluate the economics of the Two-Stage Coal Combustion Process, a process simulation computer program was prepared for the process as shown in Figure 15. This program determines the energy and material balance for a given power plant size and set of operating conditions. Operating conditions such as coal composition, slag basicity (ratio of CaO to SiO_2 + Al_2O_3), the fraction of sulfur in the slag, and the flux composition can be varied in the program. Incorporated in the simulation program are subprograms which also allow the capital and operating costs of the Two-Stage Coal Combustion Process to be estimated.

For cost estimating purposes, process equipment has been grouped into various equipment complexes--coal preparation, slag preparation, flux preparation, desulfurization, combustor, and air preparation. The equipment breakdown for these complexes and the capital and operating cost estimating procedure are presented in the Appendix.

For a 1000 MW power plant operation, the important process stream rates are shown in Table II for a 3.6 percent sulfur, 14,5 percent ash, 12500 BTU/lb heating value coal. The estimated fixed capital requirement for the Two-Stage Coal Combustion Process, retrofitted into a existing facility, is shown in Table III and seen to be $23.33 MM or $23/KW (1980).

Because the combustor is essentially a coal gasifier, it can be used to produce a hot combustible gas from coal as a feed for a gas-fired boiler.

TABLE 2

Stream Quantities for Two-Stage Coal Combustion Process*
(1000 MW Power Plant)

Stream	Ton/Hr
IN	
Coal from Coal Preparation	361
Combustor Air (Injection plus Combustion Air)(1182°F)	1222
Limestone	24
Slag to Combustor (From Desulfurization)	104
OUT	
Sulfur Bearing Slag to Desulfurization	166
Combustor Offgas to Steam Generation (2500°F)	1418
Iron	6
Sulfur	13
Desulfurized Slag (To Storage and Sale)	60

*Operating Conditions:
14.5% Ash, 3.6% Sulfur in Coal; 0.1 Slag Basicity, 8% Sulfur Slag

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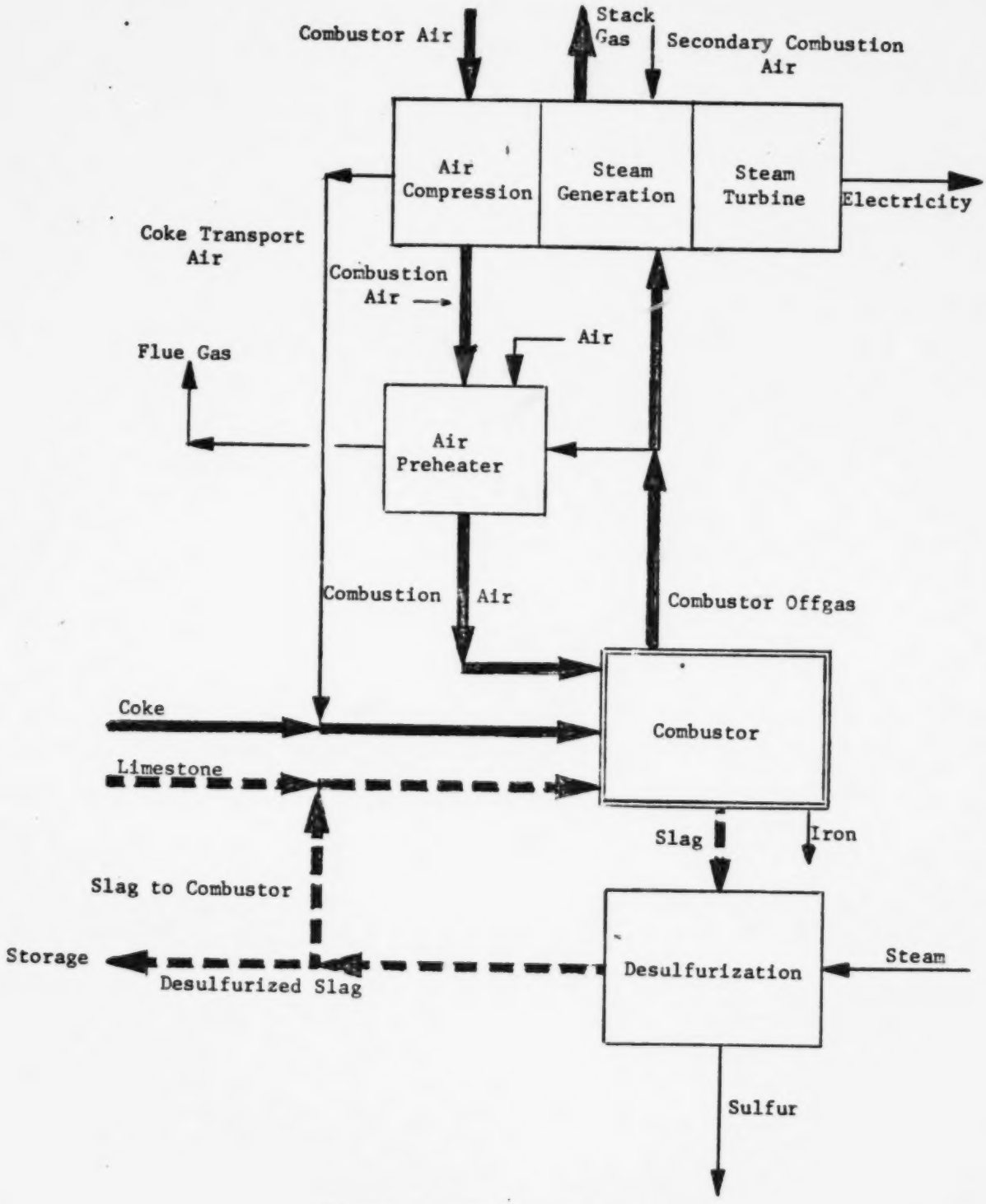

FIGURE 15 - PROCESS FLOW DIAGRAM

TABLE 3

Estimated Fixed Capital Requirement
Two-Stage Coal Combustion Process
1000 MW Power Plant

	EQUIPMENT COMPLEX	$MM
	Coal Preparation	1.83
	Slag Preparation	0.32
	Flux Preparation	0.10
	Air Preparation	2.48
	Combustor	1.71
	Desulfurization	0.60
1.	Total Purchased Equipment Cost	7.04
	Installation, Piping, Electrical Instrumentation, Utilities (70% of 1)	4.92
2.	Physical Plant Costs	11.96
	Engineering and Construction (30% of 2)	3.59
3.	Direct Plant Cost	15.55
	Contingency (10% of 3)	1.56
	Contractor's Fee (6% of 3)	0.93
4.	T O T A L	18.04
	Escalation to 1980 (14.75% of 4)	2.66
5.	T O T A L	20.70
	Interest During Construction (12.6% of 5)	2.63
6.	T O T A L F I X E D C A P I T A L (1980)	23.33

For this reason, a comparison was made of the investment required and operating costs for two types of grass root plants: (1) coal-fired boiler without SO_2 control, and (2) gas-fired boiler with combustor supplying hot gas from a coal feed. It is expected that the hot combustor offgas can be fired in a natural gas boiler with a minimum of modifications.

To estimate the fixed capital requirement for a grass roots 1000 MW Two-Stage Coal Combustion Power Station, power plant fixed capital costs were obtained[4]. These costs are shown in Table III for coal-fired and gas-fired boiler operations producing 3500 psig - 1000°F steam. Costs were determined using the standard FPC costing procedure. As seen, the total fixed capital requirement for the coal and gas-fired plants are $163.2 MM and $139.5 MM, respectively, and differ because of boiler plant equipment costs and an oil burning standby facility included in the gas-fired plant. To establish the cost of a Two-Stage Coal Combustion Power Station, the capital cost of Table III was combined with the gas-fired fixed capital requirement. As seen in Table IV, the capital requirement if $163.2 MM and $162.8 MM for the coal-and gas-fired facilities. On a dollar per kilowatt basis, the Two-Stage Coal Combustion Power Station results in a net cost increase of only $1.5/KW.

The estimated operating costs (shown in Table V) for the above power plants are 6.57 and 6.40 mills/KW hr, if by-product credits are taken in the ATC process. Without by-product credits for sulfur (420/ton), iron ($20/ton) and slag ($0.5/ton), the operating costs are respectively 6.57 and 6.82 mills/KW hr. The conventional coal burning plant is, however, introducing SO_2 into the atmosphere. Incorporation of SO_2 abatement equipment would probably add at least $25/KW to the cost of the conventional coal plant bringing the operating cost to 7.14 mills/KW hr. Thus, the Two-Stage Coal Combustion Process becomes extremely attractive in comparison--even if no by-product credits are taken (operating cost = 6.83 mill/KW-hr).

Table VI shows the effect of coal composition on a number of process variables and on operating cost. Three coals were used and classified as high, medium, and low ash. The important conclusions from Table VI are:

1. The air preheat temperature range is 1000 - 1200°F.
2. The capital requirement for a Two-Stage Coal Combustion Process plant is essentially independent of coal composition and is about $23/KW.
3. The net capital cost increase of a Two-Stage Coal Combustion Process - power plant over a conventional coal burning facility is essentially independent of coal composition and equal to approximately $1.5/KW.

4. The operating cost ranges from a high of 6.73 mills/KW hr for the high ash coal to a low of 6.40 mills/KW hr for the medium ash coal.

Other important economic conclusions which have resulted from the process simulation are:

1. Coals with as low a moisture content as practical (1-1 1/2%) should be used to reduce operating cost and air preheat temperature requirements.

2. Limestone, lime or combinations of the two can be used to flux the coal ash; however, a minimum amount of lime should be used to minimize operating cost.

3. Both process operating cost and air preheat temperature increase as the slag basicity increases. Based on experimental results to date, a minimum slag basicity of 0.1 yields operable slags and was selected to minimize operating cost.

4. Experimental results indicate that operable combustor slags containing as high as 8 percent sulfur can be used. Since both the operating cost and air preheat temperatures increase with decreasing slag sulfur content, 8 percent sulfur slags are preferred. However, even down to as low as 4 percent sulfur in the slag, the operating cost is not significantly increased.

TABLE 4
Estimated Capital Requirements
For 1000 MW Power Plant Systems
All Figures in $ Thousand

		Conventional Coal Burning	Gas-Fired Boiler* With Combustor
	Land and Rights	30	30
	Structure and Improvements	9,107	7,582
	Boiler Plant Equipment	55,492	39,200
	Turbine-Generators	34,612	34,612
	Electrical Equipment	10,138	10,138
	Misc. Power Plant Equipment	463	463
	Station Equipment	1,572	1,572
1.	TOTAL	111,414	93,597
	Other Expense (12.5% of 1)	1,393	1,250
2.	TOTAL	112,807	94,847
	Eng.-Design-Const.-Super., Contingency (12% of 2)	13,537	12,436
3.	TOTAL	126,344	107,283
	Escalation (1980) (14.75% of 3)	18,636	15,824
4.	TOTAL	144,980	123,107
	Interest During Construction (12.6% of 4)	18,267	15,511
5.	TOTAL	163,247	138,618
	Standby Oil Facility	0	1,725
6.	TOTAL	163,247	139,485
	Two-Stage Coal Combustion Plant Cost	0	23,334
7.	TOTAL	163,247	162,819
	Net MW Output	1,012	1,000
	Capital Cost $/KW	161.3	162.8

Note: All cost and factors, except coal combustion process cost, from Reference 4.

TABLE 5

Estimated Operating Cost

1000 MW Power Plants

All Figures in Mills per Killowatt-Hour

	Conventional Coal Burning	Natural-Gas-Coal Combustion Process
Capital Charge (14% Rate)	8.683	3.717
Operating, Supplies and Maintenance	0.323	0.326
Coal ($0.3/MM BTU)	2.567	2.710
Limestone ($3/Ton)	0	0.068
Iron Credit ($20/Ton)	0	(0.129)
Slag Credit ($0.5/Ton)	0	(0.025)
Sulfur Credit ($20/Ton)	0	(0.263)
TOTAL POWER COST Mills per Kilowatt Hour	6.572	6.403
TOTAL POWER COST Without By-Product Credits	6.572	6.820

TABLE 6

Effect of Coal Composition on Operating and Economic Data*
(1000 MW Power Plant)

Coal (Ultimate Analysis)	High Ash	Med Ash	Low Ash
Total Carbon	62.6%	68.1%	74.6%
Hydrogen	5.0	5.0	5.0
Oxygen	7.3	7.3	7.3
Nitrogen	1.5	1.5	1.5
Sulfur	3.6	3.6	3.6
Ash	20.0	14.5	8.0
Higher Heating Value, 1% Moisture, BTU/lb**	11700	12500	13500
Air Preheat Temperature, F	1200	1182	1015
Coal, TPH	390	361	350
Limestone, TPH	9	24	12
Lime, TPH	16	0	0
Sulfur Bearing Slag to Desulfurization, TPH	178	166	159
Combustor Offgas to Steam Generation, TPH	1395	1418	1443
Combustor Air, TPH	1202	1222	1240
Sulfur Produced, TPH	14	13	13
Iron Produced, TPH	7	6	6
Slag Produced, TPH	100	60	30
Coal Combustion Process Plant Cost, $MM	23.49	23.33	23.16
Power Plant Cost, Gas-Fired Boiler Plus Combustor $/KW	162.98	162.82	162.65
Power Plant Cost, Coal Fired Boiler, $/KW	161.31	161.31	161.31
Net Increase in Power Plant Cost, $/KW	1.67	1.51	1.34
Cost of Coal at $0.30/MMBTU, $/Ton	7.02	7.50	8.11
Operating Cost, Conventional Coal Burning Boiler, Mills/KW-HR	6.57	6.57	6.57
Operating Cost - Mills/KW-HR ($0.30/MMBTU Coal)			
With By-Product Credit	6.73	6.40	6.48
Without By-Product Credit	7.19	6.82	6.87

*2500°F Combustor Temperature, 0.1 Slag Basicity, 8% Sulfur Slag

**Dulong's Equation

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